

Wu D, Jalal AS, Baker N.

[A coupled model of the Linear Joule Engine integrated with a tubular permanent magnet linear alternator.](#)

In: The 8th International Conference on Applied Energy (ICAE2016). 2016, Beijing, China.

Copyright:

This is the author's manuscript of a paper that was presented at *The 8th International Conference on Applied Energy (ICAE2016)*, held 8-11 October 2016, Beijing, China

DOI link to article:

<http://www.applied-energy.org/icae2016/#hero1>

Date deposited:

12/01/2017



This work is licensed under a
[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](#)

A coupled model of the Linear Joule Engine integrated with a tubular permanent magnet linear alternator

Dawei Wu ^{a *}, Aslan Sa Jalal ^b, Nick Baker ^b

^a *School of Marine Science and Technology, Newcastle University NE1 7RU, UK*

^b *School of Electrical and Electronic Engineering, Newcastle University NE1 7RU, UK*

Abstract

Linear Joule Engine uses double acting free piston mechanism in its split compression and expansion cylinders, which decreases friction losses in comparison of crankshaft engines, and increases compression and expansion efficiencies in comparison of rotary heat engines. The penalty of the setup, especially split cylinders, is the increased volume of the engine. To keep a couple kilowatt engine generator in a compact size, it is proposed to integrate a permanent magnet linear alternator fully into the compressor of the Linear Joule Engine. The double acting piston in the compressor has embedded permanent magnet and works as the translator, while the compressor cylinder bore is mounted with coils as the stator. In the paper, a coupled dynamic model of the Linear Joule Engine and the integrated linear alternator is firstly presented. The coupled model bridges mechanical and electrical parts of the novel engine generator, and provides dynamic performance prediction of the design.

© 2016 The Authors. Published by Elsevier Ltd.

Selection and/or peer-review under responsibility of ICAE

Keywords: Linear Joule Engine, Double acting free piston, Permanent magnet linear alternator, Coupled model

1. Introduction

Most heat engine technologies suffers efficiency penalty when size goes down to couple kilowatts. Also, two major prime movers, internal combustion engine and combustion turbine, have inherent difficulties to be converted to use renewable sources. The Linear Joule Engine generator is an alternative technology powered with renewables and has high efficiency in micro-scale. In the previous study [1], it is estimated to have a thermal efficiency of 32.2%. However, the previous model applied a damper to simulate the performance of linear alternator as most literatures did, which weakens the credibility of the predicted performance. In this paper, a coupled dynamic model of the Linear Joule Engine and the integrated linear alternator is introduced and realized using Siemens LMS Imagine.Lab AMESim, together with Simulink, which aims to obtain pragmatic simulated results for further work on design optimization.

* Corresponding author. Tel.: +44-191-208-8113

E-mail address: dawei.wu@ncl.ac.uk

2. Development of the Linear Joule Engine Generator

The first design of the Linear Joule Engine was presented by Wu and Roskilly [1], shown in Figure 1. The split compression and expansion cylinders are placed at left and right hand sides of the prototype, whilst the linear alternator is placed in the center with its shaft coupling with the rods from the compressor and the expander. The overall length of the engine generator has to be at least three stroke amplitude plus the length of the translator and the gaps left for couplings and bearings. With the optimal stroke length of 120 mm generated from the previous simulation [1], the Linear Joule Engine Generator needs to be 400 to 500 mm long.

To reduce the overall length of the machine, the translator of the linear alternator is considered to be integrated into the compressor piston. Instead of using the expander piston, we appreciate much lower temperature of the compressor cylinder, which allows the maximum generation of the flux from the permanent magnets. As shown in Figure 2, a hollow piston is applied in the compressor, on the sleeve of which the permanent magnets are mounted in an axial formation. The study [2] in Finite Element Analysis was carried out to identify the minimum magnetic flux, magnet weight and coil numbers to produce couple kilowatts electricity. In the study [3], important design parameters of linear alternator was presented.

In most literatures discussing free piston engine or linear alternator, two parts of the machine, i.e. mechanical and electrical systems, are separately designed and optimized, therefore, it is impossible to observe dynamic interaction between two systems during the operations in simulation. It is important that a coupled model including both mechanical and electrical systems needs to be built up for accurate performance prediction and optimal engine generator design. It is noticed that a very simplified damper model is used in the study [1] to mimic the behavior of the linear alternator. A scrutiny why a simple damper cannot represent a linear alternator will be conducted using both simulated results.

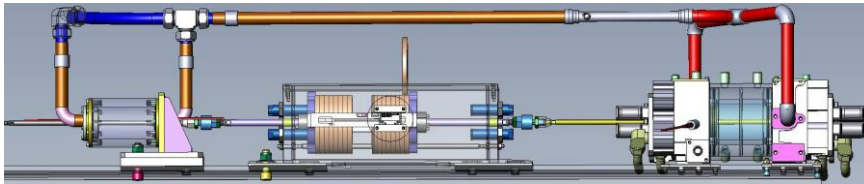


Figure 1. The first design of the Linear Joule Engine prototype [1]

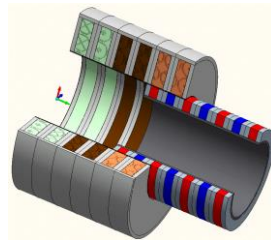


Figure 2. 3D schematic diagram of the integrated linear generator [3]

3. Modelling of the Linear Joule Engine Generator

3.1 The Linear Joule Engine model

The linear Joule Engine has four separated cylinders, two in the compressor and the other two in the expander. The real processes in the cylinders deviate from the theoretical processes in Joule Cycle, therefore universally applicable mass balance and energy balance are set up for each cylinder. The following equation describe the mass balance of the working gas in one expander cylinder, which considers the mass flow rate of the intake and the exhaust:

$$\frac{dm_{ep}}{dt} = \sum \dot{m}_{v_{ep}} \quad (1)$$

$$V_{ep} \cdot \left[\left(\frac{\partial \rho_{ep}}{\partial P_{ep}} \right)_T \frac{dP_{ep}}{dt} + \left(\frac{\partial \rho_{ep}}{\partial T_{ep}} \right)_P \frac{dT_{ep}}{dt} \right] + \rho_{ep} \cdot \frac{dV_{ep}}{dt} = \sum \dot{m}_{v_{ep}} \quad (2)$$

The governing equation of energy balance for the working gas in one expander cylinder coming from the First Law of Thermodynamics is given as:

$$\frac{dU_{ep}}{dt} + \frac{dW_{ep}}{dt} = \frac{dQ_{ep}}{dt} + \sum \dot{m}_{v_{ep}} \cdot h_{v_{ep}} \quad (3)$$

$$\left[m_{ep} \cdot \left(\frac{\partial h_{ep}}{\partial P_{ep}} \right)_T - V_{ep} \right] \frac{dP_{ep}}{dt} + m_{ep} \cdot \left(\frac{\partial h_{ep}}{\partial T_{ep}} \right)_P \frac{dT_{ep}}{dt} + h_{ep} \cdot \sum \dot{m}_{v_{ep}} \quad (4)$$

$$= k_{ep} \cdot A_{ep} \cdot (T_g - T_{ep}) + \sum \dot{m}_{v_{ep}} \cdot h_{v_{ep}}$$

In the practical application, the ranges of temperature and pressure are 300-1000K and up to 10 bar respectively, therefore ideal gas model is adequate to represent the working gas. When the ideal gas model is applied, enthalpy of the working gas is the function of temperature only. Therefore, the partial derivation items of enthalpy as the function of pressure are literally zero in this model.

The equations abovementioned is also applicable to the compressor cylinders. Only the subscripts *ep* (standing for expander) needs to be replaced. Then, four sets of mass and energy balances of four cylinders can be set up, whilst the variable differentiate two cylinders in the expander or the compressor is the piston displacement *x*, which eventually affects the cylinder volume *V*. Another variable is the timing of the valve opening, which reflects on the mass flow rate of intake or exhaust, $\dot{m}_{v_{ep}}$.

The heat transfer coefficient *k* is calculated using the equations from the study [4]. Two parts of convection heat transfer are determined separately, which are the convection heat transfer between gas and horizontal wall in the cylinders and that between gas and vertical cylinder wall.

$$h_{g_wall1} = 0.0166 Pr \cdot Re^{0.8} \cdot \frac{K_g}{R} \quad (5)$$

$$h_{g_wall2} = 0.022 Re^{-0.2} Pr^{-0.5} \cdot \left(\frac{T_g}{T_w} \right)^{-0.5} \rho C_p u_{mean} \quad (6)$$

$$Re = \frac{\rho u_{mean} R}{\mu} \quad (7)$$

$$Pr = \frac{C_p \mu}{K_g} \quad (8)$$

Two heat transfer coefficients are estimated as 101.83W/m² K and 128.59 W/m² K, which is lower than that of internal combustion engine due to lower maximum in-cylinder temperature and pressure.

The crucial components attached onto the cylinders in the design are the valves, which use the model with the discharge coefficient from Perry's experiments to determine the mass flow rates.

$$\dot{m}_{v_{ep}} = A_o \cdot C_d \cdot C_m \cdot \frac{P_{up}}{\sqrt{T_{up}}} \quad (9)$$

Finally, a dynamic balance is built on the moving mass *M* which includes one expander piston, one compressor piston mounted with permanent magnets, and the rods connecting them. The equation as:

$$F_{ep} + F_{cp} + F_{la} + F_{fr} = M \cdot \frac{d^2 x}{dt^2} \quad (10)$$

where *F_{ep}* and *F_{cp}* can be calculated via pressure differences, *F_{la}* from the linear alternator will be derived in the next section, and *F_{fr}* is the overall friction force on the moving mass, expressed as:

$$F_{fr} = f_{vc} + f_{wd} + f_{co} \quad (11)$$

$$F_{fr} = \mu_{vs} \cdot v + c_{wd} \cdot v \cdot |v| + f_{co} \quad (12)$$

where μ_{vs} is the coefficient of viscous friction in N/(m/s); c_{wd} is the coefficient of windage in N/(m/s)²; f_{co} is the Coulomb friction force in N.

3.2 The model of a tubular permanent magnet linear alternator

The linear alternator is driven by the force generated from the thermodynamic Joule Cycle. Two paramount input variables for the linear alternator is the piston velocity, i.e. the translator velocity, and the aggregated force from the working gas in the cylinders. The linear alternator is not only a passive ‘slave’ machine, which has its way to affect the dynamic balance of the linear motion of the Linear Joule Engine via the responding forces during the electricity generation. The responding forces include six parts shown in the equation below:

$$F_{la} = F_{ele} + F_{cog} + F_{co} + F_{ed} + F_{cp} + F_{ar} \quad (13)$$

F_{ele} is the electrical corresponding force, which is the major part in quantity of the responding forces. F_{cog} is the cogging force in permanent magnet linear alternators, which is generated due to the reluctance variation brought by the stator tooth. Magnetic core loss includes hysteresis loss P_h which is a heat loss caused by molecular friction of the magnetic particles of the core. The other part of the magnetic core loss is eddy current loss P_e due to currents induced in any conductor, e.g. the iron core, when it is moving in a magnetic field. The force F_{co} represents the above two parts of the magnetic core loss, which varies with the electrical frequency derived from the piston/translator velocity. The permanent magnets have the same effect as any conductor, in which the eddy current loss is generated as well. F_{ed} represents the eddy current loss P_{em} only in the permanent magnets. The power lost in the form of heat in the armature winding of a generator is known as Copper loss. The equivalent force representing the loss is written as F_{cp} . The term F_{ar} represents the armature reaction force, which is due to machine current loading. It varies with current loading and the translator position with repetition cycles equal to the number of machine phases over translator pole. The responding forces from the armature circuits are expressed in details as follows. EMF stands for Electromotive force, which is denoted and measured in volt.

$$EMF_{i \in (a,b,c)} = -N \cdot 2\pi f_{ele} \cdot \hat{\Phi} \cdot \cos\left(\frac{\pi}{\tau_{pp}} x\right) \cdot v \quad (14)$$

$$EMF_{i \in (a,b,c)} = I_i(R_L + R_i) + L \frac{dI_i}{dt} \quad (15)$$

$$F_{ele}(\dot{x}, I_i) = \sum_{i \in (a,b,c)} I_i^2 \cdot R_L / v \quad (16)$$

$$F_{cp}(\dot{x}, I_i) = \sum_{i \in (a,b,c)} I_i^2 \cdot R_i / v \quad (17)$$

$$F_{ar}(x) = \hat{F}_{re} \cdot \sin\left(\frac{m \cdot \pi \cdot x}{\tau_{pp}}\right) \quad (18)$$

The cogging force over one translator pole as a function of piston/translator displacement x is given as follows. It is periodic depending on the number of stator slots and the translator poles. The symbols (S, T_p, τ_{pp}) are the number of slots, the number of translator poles and translator pole pitch, respectively. The (\pm) sign in phase shift (ϑ_c) holds for oscillating motion of the translator, and the phase shift represents the shift from position corresponds to peak cogging force of total moving translator with respect to the stationary stator, where: $0 \leq \vartheta_c \leq 180$.

$$F_{cog}(x) = \hat{F}_{cog} \cdot \sin\left(\frac{\pi}{\tau_{pp}} \cdot \frac{LCM(S, T_p)}{T_p} \cdot x \pm \vartheta_c\right) \quad (19)$$

The magnetic core losses and the eddy loss of the magnets are presented aggregately as:

$$F_{co}(\dot{x}) + F_{ed}(\dot{x}) = (P_h + P_e + P_{em})/u \quad (20)$$

In the model, the peak air-gap magnetic flux $\hat{\Phi}$, the peak armature reaction force \hat{F}_{re} , and the peak cogging force \hat{F}_{cog} are estimated using Finite Element Analysis modelling [2] in order to minimise the permanent magnet cost with maximum utilisation of a specific design force and velocity.

Combined the models of the Linear Joule Engine and the tubular permanent magnet linear alternator, the power generated from the linear engine generator will be observed. The interaction between the mechanical and electrical parts can be revealed from the variations of the variables, i.e. velocity, displacement, voltage, and current, etc.

4. Results and discussions

The Linear Joule Engine applies the optimal geometry and dimensions from the study [1]. In order to mount on enough permanent magnets, 8 kg moving mass which includes two pistons, piston rods, sleeve, and permanent magnets, are applied. The engine reaches stable operation after 10 s (In the first second piston displacement is shown in Figure 3), which generates 2 kW mechanical power for electricity generation, and achieves an overall thermal efficiency of 34%. In the literature [5], it was predicted that a 5 kW Joule-cycle engine with pressure ratio of 7.5 has an overall efficiency of 33.2%, which is closed to the simulated result in this study. Some improvements may be from the free piston mechanism instead of crankshaft mechanism in the literature.

The heat addition for the Linear Joule Engine is conducted out-of-cylinder, which requires any heat sources around 790 °C. As compression and expansion happen in different cylinders, split thermodynamic cycle diagrams are concluded in Figure 4. The blue dot line indicates the pressure build-up in the compressor and the orange one shows the expansion process.

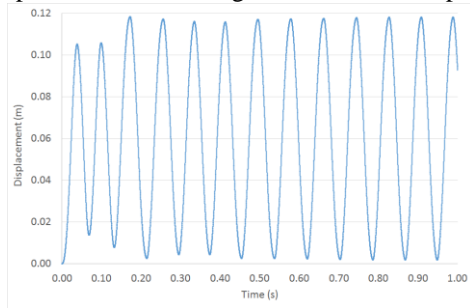


Figure 3. Piston/translator displacement in the first second

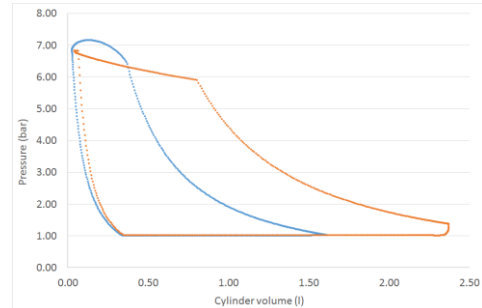


Figure 4. Pressure vs. volume diagram of the split cycle

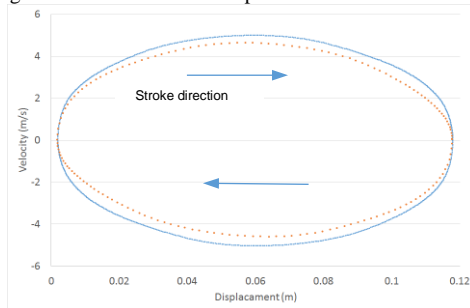


Figure 5. Piston/translator velocity profile comparison
Different models of the linear alternator affect the linear motion significantly, as shown in Figure 5.

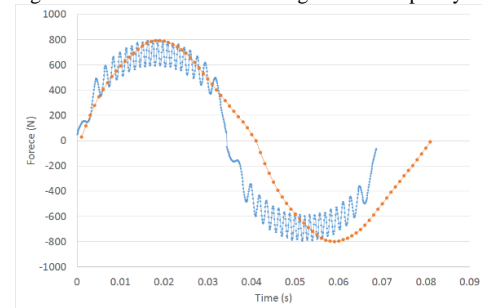


Figure 6. Responding force simulation of the linear alternator

When the same peak responding force around 800 N applied for the simplified model using a damper or the detailed linear alternator model, the top velocity of the piston-translator differs. Lower peak velocity of the simplified model also means the electricity generation is less. One possible reason is the damper creating more responding forces than a real linear alternator, which slows down the piston-translator and results in a lower mechanical frequency, in turn, lower electricity output. From Figure 5, it is also noticeable that two velocity profiles differs largely when the piston-translator comes toward the end of one stroke. The answer can be found in Figure 6. In a real linear alternator, when the translator moves out of the magnetic field, the flux disappears instantly which leads to a sharp drop of the electrical corresponding force. The simplified model just applies a proportional factor on velocity to simulate the responding forces, which cannot reflect this ‘dead-zone’, but only gives a gradually decreased force profile toward the end of a stroke.

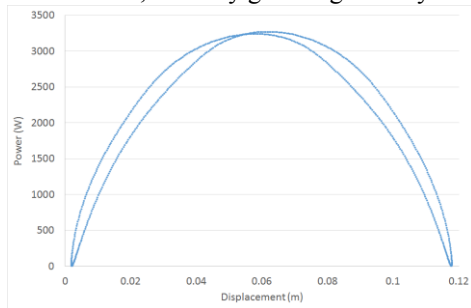


Figure 7. Power generation in one completed cycle

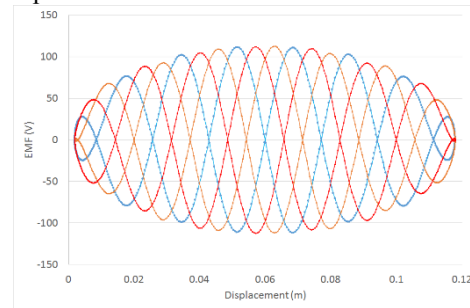


Figure 8. Three phase EMF profiles versus displacement

The Linear Joule Engine generator produces 1.8 kWe from 2 kW mechanical power input. The overall electrical efficiency of the machine is 30%. The instantaneous power generation profile in one cycle (two strokes) is illustrated in Figure 7, which reveals that more power is generated in the second half of a stroke while the velocity is relatively higher. EMF is another indicator of the alternator performance. EMF in three phases are presented in Figure 8, which clearly shows that there is 7 poles on the translator. When the pole passes the coil, that phase generates a peak EMF. The peak values are incline to get smaller toward both ends of strokes due to the lower velocity at that time.

5. Conclusions and Recommendations

The coupled model of the Linear Joule Engine generator presents a better performance prediction compared to the simplified model using a damper to simulate linear alternator. The thermal and electrical efficiency of 34% and 30% respectively for a 1.8 kWe engine powered with 800 °C heat source is proved to be achievable, which makes the machine desirable in micro-scale compared to its rival technologies. The innovative idea to combine the compressor with the linear alternator makes a compact machine, which has fully integrated mechanical and electrical parts. The next phase work is to modify the key parameters of Linear Joule Engine generator to identify the best parameter matrix for performance enhancement.

References

- [1] Wu D., Roskilly A.P. (2014) Design and parametric analysis of Linear Joule-cycle Engine with out-of-cylinder combustion. *Energy Procedia* 61, 1111 – 1114.
- [2] Jalal A.Sa., Baker N.J., Wu D. (2016) Design of tubular Moving Magnet Linear Alternator for use with an External Combustion – Free Piston Engine. 8th IET conference on power electronics, machines and drives, London.
- [3] Jalal A.Sa., Baker N.J., Wu D. (2016) Electrical Machine Design for use in an External Combustion Free Piston Engine. 5th Renewable Power Generation Conference, Glasgow.
- [4] Wang C.S., Berry G.F., (1985) Heat Transfer in Internal Combustion Engines. The American Society of Mechanical Engineers, the Winter Annual Meeting, Miami, Florida.
- [5] Moss R.W., Roskilly A.P., Nanda S.K. (2005) Reciprocating Joule-cycle engine for domestic CHP systems. *Applied Energy*, 80, 169-185.